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Development of a low-cost monitoring system for open 3d printing

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Abstract. 3D printers for Rapid Prototyping and Additive Manufacturing have been widely accepted by large and small-scale industries or by many hobbyists. Due to its nature of layer by layer addition of material, identifying defects between the layers can be a crucial strategy to determine the quality of a 3D printed product by carefully monitoring the layerwise process during part building. This kind of approach gives an advantage in the applications where 3D printing of products requires high customization without compromise on part quality. In this work, a low-cost camera is installed in an open 3D printer, and computer vision algorithms are used to implement an in-situ monitoring system. The defects can be evaluated by comparing the printed layer to the deposition path of the open ISO G-code. The G-code printing file is modified to introduce the image capture step after each layer. The value of the area of missing or exceeding material is returned to the user with the corresponding images. A decision can be made to abort the job in case of important defects to avoid unnecessary waste in material, time, and costs.

1. Introduction

Additive Manufacturing (AM) has emerged as an alternative to conventional subtractive manufacturing techniques. Successful applications of AM have demonstrated that a specific benefit should be pursued by considering more freedom in part design for AM (DfAM) [1]. AM and 3D printing sustainability has been considered in the literature from an environmental perspective [2]. Due to this, many industries have already adopted AM in their production process or research division.

Among AM technologies [3], the most widespread process is Fused Deposition Modelling (FDM), which was initially patented by Stratasys company. It is based on the deposition of a thermoplastic filament in a predefined path by the extruder on the build plate. The deposition of melted filament layer-by-layer forms a 3D object. The expiration of Stratasys patent has favoured the diffusion of a significant number of low-cost 3D printers.

With the capability of penetrating in many industrial sectors, AM can also offer process monitoring techniques to check in quality perspectives. In-situ monitoring makes the user aware of the status of ongoing printing, and could also raise flags/indication in the situation where the part fabrication deviates from ideal conditions. Detecting defects during printing allow user to minimize the material waste while reducing production costs and time. In industrial AM machines, monitoring is one of the key topics for controlling part quality with the opportunity of skipping expensive post-production non-destructive inspection (NDI) operations. Several monitoring techniques have been proposed and tested depending on the specific layer-wise process under consideration [4-9].

Many defects can occur during the 3D printing process due to irregular operation of the printing system itself or external factors. These defects can affect the final product quality in many aspects,

including mechanical and surface finish [10,11]. With the help of a monitoring system, these defects can be detected and analysed during the layer formation process. Furthermore, these defects can be classified into two main categories, that are (i) lack of material deposition or (ii) undesired material deposition.

The implementation of an in-situ monitoring system can be easily developed for open 3D printers. The design constraints for the system are that its overall cost should be less than the printer cost, and the printing process is carried out through the use of open ISO G-code. Modifications of the G-code are used for programming interaction of the in-situ monitoring system with the standard working cycle of the 3D printer in each layer.

In this paper, a low-cost in-situ monitoring system is proposed to detect presence of defects in the single layer of an open 3D printer. Defect detection is achieved by development of a simple system for image acquisition that works in parallel with the printer, while image analyses are completed using the computer vision toolbox of Matlab software. The monitoring system and methodology are described in the following section, whereas experimental results are presented in the third section. In the final section, conclusions and future developments are discussed.

2. Materials and methods

The proposed monitoring system comprises a USB camera by Svpro of model SV-USBFHD06H-SFV, an Arduino board, and two sensors.

The reason for selecting this camera was a trade-off between the resolution and the cost. The camera is equipped with a Sony IMX322 sensor and comes with the adjustable 5-50 mm varifocal lens of 1/2.9" size. It can capture images with a resolution of 2 Megapixels and generate full HD images having a size of 1920 pixels x 1080 pixels. The cost of the camera is about 85 euros, and the focus is manually adjustable. This type of camera helps to maintain the focus at the topmost layer since the bed of the 3D printer is lowered at the start of every new layer during the part build. The Arduino board collects the signal from the two sensors. The first sensor detects the layer completion, while the other is used as user input to stop the acquisition of images.

A 3d printer model A4v3 by the Italian company 3ntr was selected for developing the in-situ monitoring system through the installation of the USB camera. The printer comes with three extruders for 2.85 mm filaments and has a heated bed and a heated chamber. The print volume is 300 mm x 175 mm x 200 mm, and the firmware is a customized version of the open MarlinKimbra.

To acquire a picture of the current layer, the camera was installed on the top of the printer bed using an aluminium support bar. For this purpose, the top cover of the printer was removed, as shown in figure 1. With this configuration of the camera, the acquired images are always perpendicular to the print bed and part cross-section. This approach ensures minimal modification to the printing process and its subsystem, such as the print head.


Figure 1. Printer setup with the Svpro camera and checkerboard pattern.
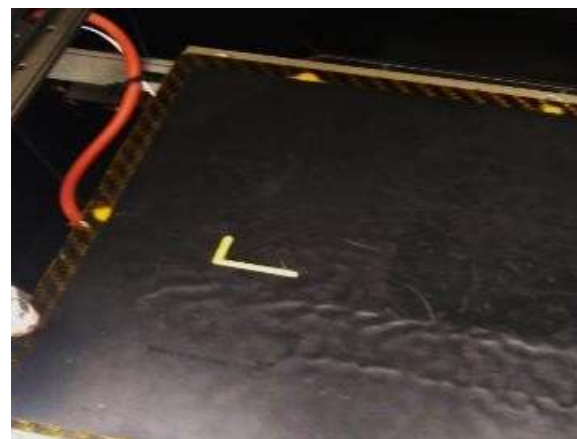
Figure 2. L-shaped reference used to align the checkerboard pattern on the print bed.

The procedure for monitoring the printing process layer after layer is summarised in the flowchart of figure 3. The steps shown in the flowchart are repeated for each layer and are introduced in the G-code file via Matlab as explained in section 3.2.
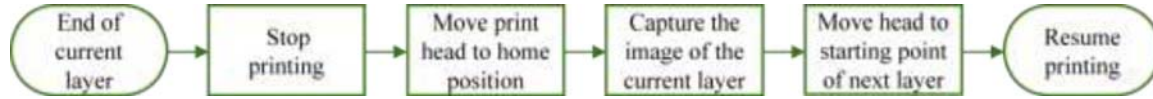
Figure 3. Monitoring system sequence for each printed layer.

2.1. System calibration

The system calibration to correct the distortion in images is implemented using a checkerboard pattern printed on plain paper (figure 1). An L-shaped 3D printed reference part is used to align the checkerboard pattern with the bed axes (figure 2). Using the procedure described by Fetic et al. [12], the camera parameters are computed starting from the acquired image of the checkerboard pattern. With the information from the G-code, the system can automatically perform adjustments to select the region of interest and recognize the positional coordinates on the printing bed.

2.2. Modification of G-code file

The G-code file is obtained by slicing the CAD model of the part in STL format using Kisslicer software. At this stage, printing parameters such as nozzle temperature, layer height, and infill density are chosen for the A4v3 printer by 3ntr company. The G-code generated by Kisslicer for the standard printing process without monitoring is analyzed line-wise, i.e. instruction by instruction via a Matlab script. The script identifies where the layer changes in the G-code by looking for the value change of the Z coordinate. At this point, to incorporate the monitoring operation at the end of each layer, the script modifies the G-code adding the image capture sequence. The modification is done by inserting the lines and instructions to complete the steps of figure 3. At first, the filament is retracted in the printer head, followed by the head being moved to the home position to ensure no optical occlusion for the camera over the latest printed layer. A sensor senses the home position at the layer end and sends the signal to capture the image during which the printer is kept in pause mode for a predefined waiting time. Subsequently, the printer head moves back to the printing position, where the retracted filament is pushed back into the nozzle to continue the printing.
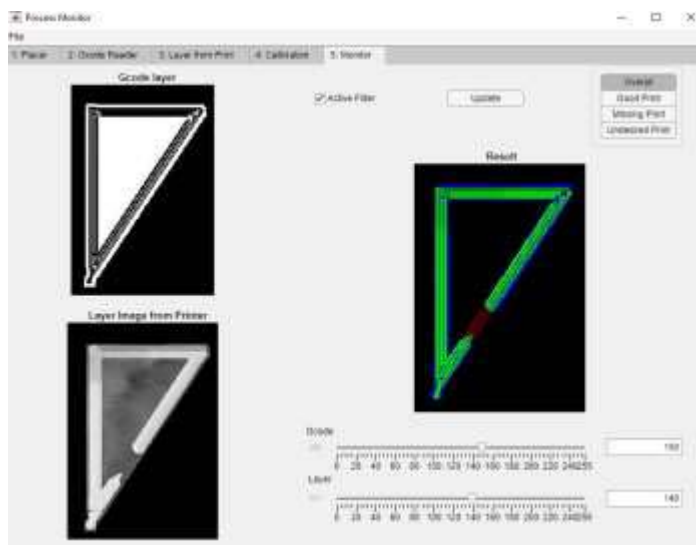
2.3. Defect detection by image analysis

The detection of 3D printing defects in each layer is done by comparing the actual layer image to its corresponding reference image. For each layer, the reference image is generated from the original G-code file. This image is formed by a marker that replicates the printing nozzle's action on a blank image and draws the printing paths. The marker estimates the width W of the deposited filament by equating the mass flowing inside and outside the nozzle by equation 1:

$$W = \pi \, (D/2)^2 \cdot E \, / \, (t \cdot d) \tag{1}$$

Where t is the layer height, and d is the travelling distance of the nozzle while printing. E and D are the length of filament to be extruded and the filament diameter before extrusion, respectively.

The marker draws the movement corresponding to each printing path with the computed width W and the drawing is repeated on a single image for each layer till all the printing instructions are extracted from G-code. The printing defects are identified through pixel-by-pixel comparison of the two corresponding images.

A specific user interface (figure 4) is designed using Matlab App Designer to show real-time information about the ongoing printing process. In case there is a presence of a defect, a corresponding flag is raised to the user. The interface reports the reference image generated from the G-code, the layer image captured by the USB camera, and the result of their comparison.

Figure 4. User interface for defect detection that was developed using Matlab.
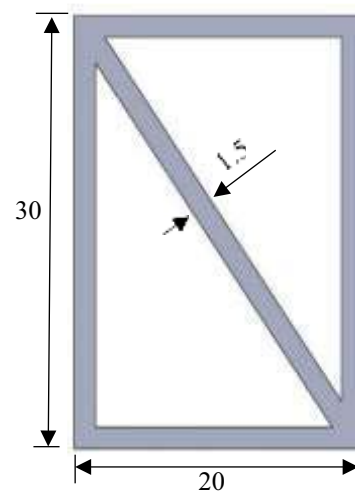
Figure 5. Geometry of the test sample with main dimensions in millimetres.

3. Experimental testing

To validate the monitoring system for the analysis of defects occurring during printing, a simple rectangular test sample (figure 5) is used. The two sides of the rectangle measure 20 mm and 30 mm respectively with a single diagonal. The sample has a thickness of 1.5 mm and its total height is 0.5 mm perpendicular to the bed. It was printed with a yellow colour filament of ABS material using the process parameters in table 1.

Table 1. Printing parameters for the test sample.

Parameter	Value
Layer height	0.3 mm
Nozzle temperature	255 ℃
Bed temperature	120 ℃

For monitoring the printing process of the test sample, the varifocal length of the USB camera was adjusted to capture a preselected region of interest with an area span of 76 mm x 57 mm on the printer bed. The resolution of the captured images was set to 800 pixels by 600 pixels. This configuration makes the system capable of detecting defects with an accuracy of 0.095 mm, i.e. approximately 10.5 pixels are associated with a length of 1 mm.

Figure 6 shows the printing path generated by Kisslicer software in the G-code file, while the reference image created with the marker from the printing path is shown in figure 7.
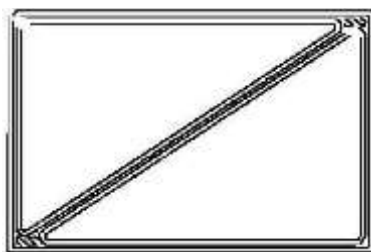
Figure 6. Printing path of the rectangular sample without considering the extrusion width.
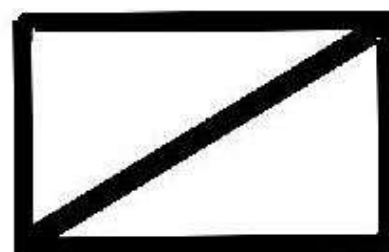

Figure 7. Reference image for the rectangular sample.

To validate the monitoring system capabilities for automatic detection of defects, a defective sample part is printed by manually decreasing the feed of the extruder head for overdeposition of ABS material. Moreover, when printing is complete, two small portions of the printed part are slashed out to generate two zones with missing material. The monitoring system captures the printed layer image with the two defects, as shown in figure 8. This image is processed and compared to the reference image of the same layer (figure 7). The overall result of the comparison is shown in figure 9, wherein the green colour is used for referring to the deposited filament that was correctly printed.

Moreover, two more images are generated to singularly identify the area corresponding to the two target defects of (i) lack of material deposition or (ii) undesired material deposition. The area of first target defect is shown in figure 10 but also visible with red colour in figure 9. The area of the second defect is shown in figure 11 but also outlined in blue colour in figure 9.
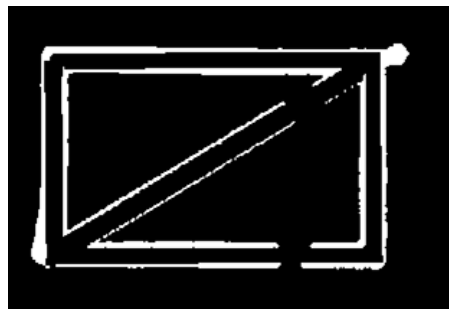
Figure 8. Printed sample with artificial defects.
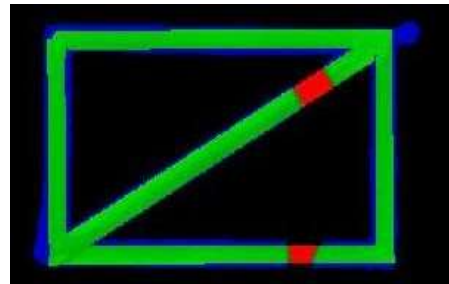
Figure 9. Result of the Process monitoring system for detection of printing defects.
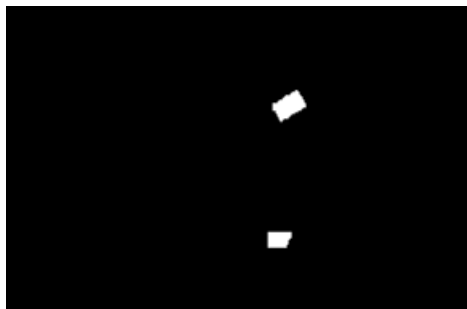
Figure 10. Lack of deposition of filament corresponding to the artificial defect.

Figure 11. Undesired filament deposition across the edges of the rectangular test sample.

With information about the system configuration and resolution, the area corresponding to each colour can also be measured. Hence, the monitoring system reports that an area of 8.7 mm^2 corresponds to the first defect of missing material. The second defect of undesired filament deposition covers an area of 77.78 mm^2 due to overextrusion.

4. Conclusions

An in-situ monitoring system was developed to detect layerwise defect formation during the 3D printing process. The system captures layer images via a low-cost USB camera installed over an A4v3 printer by 3ntr and uses computer vision for image analysis. With the addition of two sensors, the system is automated to work in parallel with the filament deposition for detecting defects at the end of each layer in ongoing 3D printing jobs.

The technique exploited by the system to monitor the printing process is simple but effective. The captured layer image of the actual current layer is compared to a reference image generated by assigning adequate thickness to the printing path described in the open ISO G-code file. The comparison is carried out pixel by pixel to detect printing defects live. Therefore, the monitoring system is also a decision-

making tool that can guide the user in stopping and aborting the 3D printing process when the detected defect is severe.

An experimental test was conducted using a rectangular-shaped test sample with a single diagonal. Both kinds of target defects as (i) lack of filament deposition and (ii) undesired filament deposition were successfully detected with the resolution of 0.095 mm. This resolution can be increased by setting the camera to full HD images of 1920 pixels x 1080 pixels. Another possibility to increase the system resolution is to adjust the focus of the camera and zoom for capturing a smaller area of the print bed.

The accuracy and performance of the developed monitoring system can be further improved in future studies. For example, the calibration procedure might be automated and the measurement of the real value of the width W of the deposited filament can be introduced in the generation of the layer reference image from the G-code file.

However, the strong points of the proposed monitoring system are the low-cost and the easy implementation in a wide range of open 3D printers. 3D information about every deposited layer can also be retrieved using stereoscopic vision, if a second camera is installed in the 3D printer with a different view direction and angle from the first one.

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